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Two Dimensional Behavior of Megagauss Field Confined Solid Fiber Z Pinches

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TWO-DIMENSIONAL BEHAVIOR OF MEGAGAUSS-FIELD-CONFINED SOLID FIBER Z-PINCHES

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INTRODUCTION

Experiments at Los Alamos [1], the Naval Research Laboratory [2], Imperial College [3], and elsewhere have demonstrated that interesting fusion plasmas can be created by discharging modern high-voltage pulsed power generators through frozen deuterium fibers or solid fibers of other materials. Fiber diameters in the Los Alamos experiments are approximately 30 μm and currents are as high as 1 MA, leading to magnetic field strengths in the vicinity of the fiber-formed plasma which may exceed 100 MG.

At Los Alamos, we have performed one-dimensional and two-dimensional magnetohydrodynamic (MHD) computations of the formation and evolution of fiber-formed plasmas. Our one-dimensional computations [4] show that current in the existing Los Alamos and Naval Research Laboratory (NRL) experiments is carried by hot plasma which has been ablated from the solid fiber. Our two-dimensional computations [5] exhibit $m = 0$ unstable behavior in the hot, exterior plasma prior to complete ablation of the solid fiber; the $m = 0$ behavior enhances the fiber ablation rate.

The MHD model used in our computations accesses the Los Alamos SESAME tabulated atomic data base computer library to determine material properties (specific energy, pressure, ionization level, electrical resistivity, and opacity). The MHD partial differential equations are solved numerically using an alternating-direction implicit (ADI) finite difference method which does not resort to fractional time steps, or "operator splitting." The computations use "cold-start" inital conditions in an attempt to compute the behavior of the pinches from $t = 0$. The two-dimensional computations begin with a 2% random variation superimposed upon the density profile of the solid core to provide perturbations for instability growth.

In this paper, the two-dimensional computations are further examined. In the computations reported here, two-different axial lengths, l, are considered, $l = 5$ mm and $l = 300$ μm, to study long- and short-wavelength behavior. The long-wavelength computations show the formation and evolution of hot spots in the hot corona surrounding the cold, solid core of the plasma channel; subsequently, hots spots form on the axis of the discharge. The short-wavelength computations exhibit a periodic re-establishment of a quasi-one-dimensional configuration.

LONG-WAVELENGTH BEHAVIOR

As discussed in [5], the long-wavelength (l=5 mm) computations exhibit $m=0$ behavior which inititates in the corona and eventually effects the high-density core. In the l=5 mm computations, the shortest wavelengths which the computational mesh can support are evident and they persist throughout the duration of the computations. The m=0 behavior alters the one-dimensional radial density and temperature profiles and introduces axial gradients in the density, temperature, and other quantities.

Figures 1 and 2 show temperature and density contours, respectively, in the r-z plane for HDZP-I, the existing Los Alamos experiment (250 kA, 200 ns), at 21 ns, a time significantly earlier than the time of complete fiber ablation (55 ns). Fig. 1 shows that temperatures higher than 100 eV occur in hot spots which are centered at a radius of approximately 90 μm, 6 times the radius of the initial fiber. A comparison of Fig. 2 with Fig. 1 shows that the hot spots occur at the "necks" of the $m=0$ instability where current is localized.

An examination of the 100 ev temperature contour in the computations at times beyond that of Figures 1 and 2 shows that the center of the hot spots moves radially inward to approximately 60 μm at 24 ns, then moves radially outward as the hot spots increase in radial extent. On occasion, a neck of the instability constricts and splits the corresponding hot spot into two spots which move axially apart as the constriction drives radially inward.

As the fiber ablation proceeds, the hot spots which surround the cold core disappear and hot plasma is formed on the axis of the discharge. Because of the $m=0$ behavior, the temperature on axis is not uniform and hot spots appear. Temperature contours just prior to complete fiber ablation are shown in Fig. 3. Temperatures greater than 5 keV occur in spots less than 1 mm away from very cold material ($<$ 10 eV) which is the remnant of the solid fiber.

Long-wavelength (l=5 mm) computations for the existing NRL experiment [2] are qualitatively similar to those shown in Figures 1-3. Even though the NRL current and dI/dt are larger than for HDZP-I, the fiber diameter (125 μm) is also larger, so that the $m=0$ growth times and fiber ablation times are correspondingly larger.

Long-wavelength computations for HDZP-II, the Los Alamos facility presently becoming operational (1.2 MA, 100 ns), are also qualitatively similar. However, the computations predict that the fiber will ablate in 11 ns or less and not persist for a significant fraction of the duration of the experiment. Prior to fiber ablation, hot spots having a temperature exceeding 250 eV begin to appear at approximately 9.5 ns at a 30-40 μm radius (less than three times the initial fiber radius).

SHORT-WAVELENGTH BEHAVIOR

Whereas the long-wavelength (l=5 mm) computations show the formation and persistence of the shortest wavelength modes that the computational mesh can support,

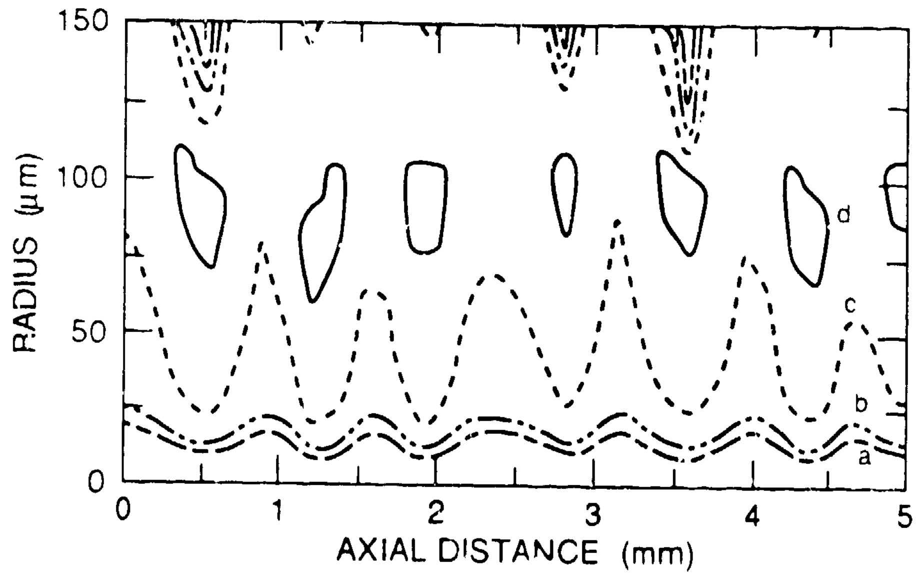

Fig. 1. Temperature contours in the r-z plane at 21 ns for HDZP-I ($r_f = 15\ \mu m$, $\rho_f = 0.5\ \rho_s$). The contour values are (eV): (a) 10; (b) 25; (c) 50; (d) 100.

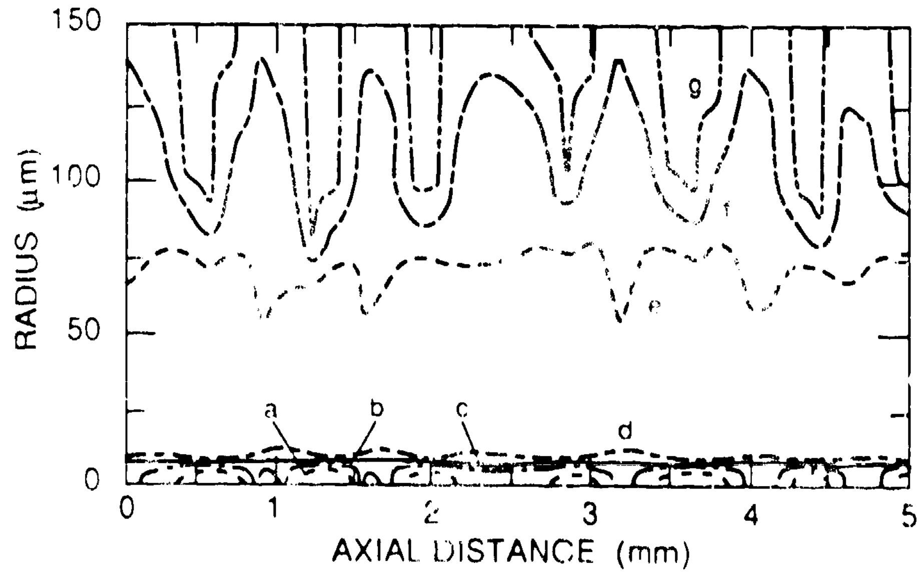

Fig. 2. Mass density contours in the r-z plane at 21 ns for HDZP-I ($r_f = 15\ \mu m$, $\rho_f = 0.5\ \rho_s$). The contour values are (kg/m^3): (a) 263; (b) 180; (c) 129; (d) 64; (e) 0.2; (f) 0.08; (g) 0.01. One-half of the total mass lies within contour (c) and 20% lies outside contour (e).

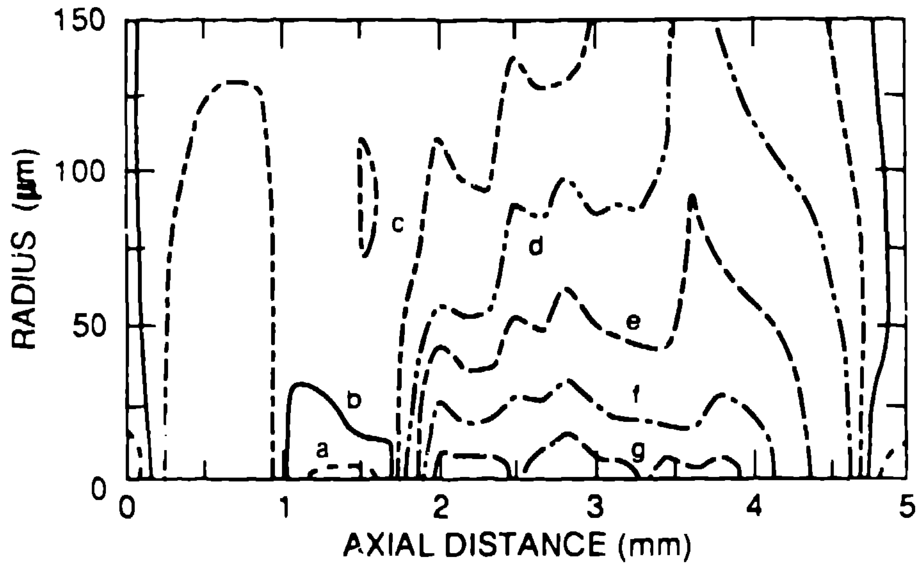

Fig. 3. Temperature contours in the r-z plane at 53 ns for HDZP-I ($r_f = 15$ μm, $\rho_f = 0.5\ \rho_s$). The contour values are (eV): (a) 25; (b) 100; (c) 250; (d) 500; (e) 1000; (f) 2500; (g) 5000.

the shortest wavelengths which appear in $l = 300$ μm computations saturate and longer wavelengths become dominant.

Figures 4 and 5 show density contours from HDZP-II computations at a time prior to and just after total fiber ablation, respectively. In Fig. 4, short-wavelength behavior is evident to some extent in the high density core of the discharge, but a longer wavelength is dominant in the surrounding corona. Fig. 5 shows the establishment of a 200-μm-long, nearly one-dimensional section at the right-hand side of the figure (exactly horizontal contours would indicate a precisely one-dimensional configuration). The quasi-one-dimensional section is subsequently disrupted by $m = 0$ constrictions, after which the dynamics seem to be approaching a re-establishment of a one-dimensional configuration.

CONCLUDING REMARKS

Our initial two-dimensional computations which are discussed here and in Ref. 5 suggest that fiber-formed z-pinches are $m = 0$ unstable. The formation of hot spots at the boundary of a plasma which is significantly larger than the initial fiber diameter (Figures 1 and 2) is qualitatively similar to experimental observations at Imperial College [3]. The development of hot spots on axis (Fig. 3) is qualitatively similar to experimental observations reported by Los Alamos [1] and NRL [2]. The establishment of a quasi-one-dimensional configuration (Fig. 5) may explain why experimental diagnostics which have been implemented to date appear to indicate the presence of a stable plasma.

Only further experimentation and diagnostic development (and, of course,

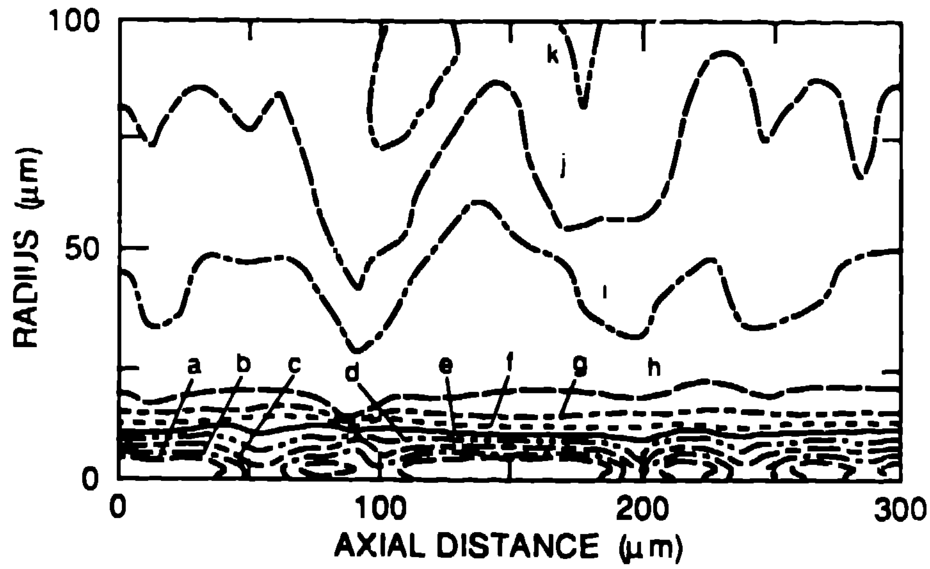

Fig. 4. Mass density contours in the r-z plane at 4 ns for HDZP-II (r_f=15 µm, ρ_f=0.5 ρ_s). The contour values are (kg/m^3): (a) 165; (b) 127; (c) 98; (d) 75; (e) 55; (f) 39; (g) 24; (h) 7; (i) 0.6; (j) 0.2; (k) 0.01. One-half of the total mass lies within contour (c) and one-tenth of the mass is contained within each set of adjacent contours except (i)-(j) and (j)-(k).

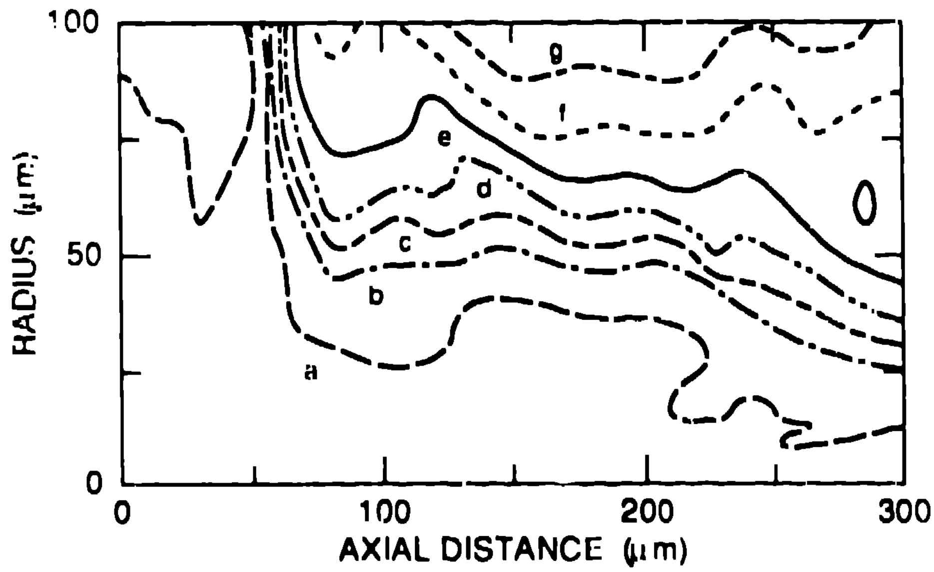

Fig. 5. Mass density contours in the r-z plane at 12 ns for HDZP-II (r_f 15 µm, ρ_f 0.5 ρ_s). The contour values are (kg/m^3). (a) 0.19; (b) 0.15; (c) 0.13; (d) 0.12; (e) 0.09; (f) 0.07; (g) 0.06. One-half of the total mass lies within contour (e) and one-tenth of the mass is contained within each set of adjacent contours.

additional computations and analysis) can determine whether or not the computations reported in this paper are qualitatively and quantitatively valid. Should the computations prove to be valid, then experimentation and computation will need to study in detail the long-term evolution of unstable behavior. It seems quite possible that, at the high densities and short time scales characteristic of the fiber-formed pinches, unstable behavior is not necessarily fatal in a fusion context.

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